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David J. Diamond

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Nuclear Energy and Infrastructure Systems Division/NE

Brookhaven National Laboratory

P.O. Box 5000
Upton, NY 11973-5000
www.bnl.gov

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Requirements for reactor physics design

David J. Diamond^{a*}

^a *Brookhaven National Laboratory, Upton, USA*

Abstract

It has been recognized that there is a need for requirements and guidance for design and operation of nuclear power plants. This is becoming more important as more reactors are being proposed to be built. In parallel with activities in individual countries are norms established by international organizations. This paper discusses requirements/guidance for neutronic design and operation as promulgated by the U.S. Nuclear Regulatory Commission (NRC). As an example, details are given for one reactor physics parameter, namely, the moderator temperature reactivity coefficient. The requirements/guidance from the NRC are discussed in the context of those generated for the International Atomic Energy Agency. The requirements/guidance are not identical from the two sources although they are compatible.

1. Introduction

In the nuclear power industry, there is a need for standards (or requirements or guidance) to help assure that the product is of high quality and meets acceptable levels of safety. Power reactor requirements/guidance have been developed in most countries operating such plants as well as in international organizations such as the International Atomic Energy Agency (IAEA). The interest in building new reactors throughout the world means that attention has to again focus on standards for design and operation. In some countries that have no history of building power reactors (e.g., Turkey) or are considering totally different technologies relative to past experience (e.g., Canada), the issue of requirements/guidance becomes more pressing. In the United States (U.S.), an interest in improving

the licensing process has led the Nuclear Regulatory Commission (NRC) to consider requirements/guidance in a risk-informed and performance-based framework (Drouin, 2007). This framework could be applied to evolutionary reactors or to designs that the NRC has yet to consider.

In order to help understand how requirements/guidance emanate from the regulatory agency and how they relate to international norms, consider requirements and guidance for reactor physics (or equivalently, neutronic) design as promulgated by the NRC. These impact not only how the reactor should be built, but also how it is operated. Neutronic design refers to having an acceptable power distribution within the core, to the design and use of reactivity control systems for normal operation and for shutting down the reactor, to stability, and to the various reactivity feedback

* Corresponding author, diamond@bnl.gov

Tel: +1 (631) 344 2604; Fax +1 (631) 344 3957.

characteristics. This example from the U.S. can help guide what might be done in the future in other countries as well as what might be done in the U.S. with new requirements/guidance. The discussion is also consistent with recent efforts to normalize requirements internationally (Reig, 2008) albeit that effort has not yet considered neutronic design.

In the following sections an overview of the requirements and guidance in the U.S. is presented and the moderator temperature reactivity coefficient (MTC) is used to provide an example of how the requirements/guidance apply to a specific neutronic parameter. The connection to the approach by the IAEA is then given. Lastly, some general comments are presented.

2. The approach in the U.S.

2.1. General approach

The approach taken by the NRC consists of requirements for reactor design that are rather general and guidance to the licensees on how to proceed, with that guidance in some instances being very specific and quantitative. After years of experience, which includes the licensing of more than 100 units, multiple reloads at each unit, numerous design changes, and several design certifications of proposed nuclear power plants, this guidance has become synonymous with requirements.

The resulting design is documented by the licensee in its Safety Analysis Report (SAR) which becomes a part of the licensing basis. The design is verified through testing that is specified in the SAR and the Technical Specifications (Tech Specs), and through the NRC inspection process.

The general approach is shown schematically in Figure 1 and applies to reactor design, not just the neutronic or reactor physics design. The high level design requirements are specified in Title 10 Code of Federal Regulations, Part 50 (10CFR50), Appendix A, entitled General Design Criteria (GDC).^{*} The guidance that is used to implement the GDC is found in several places but most notably in the Standard Review Plan (SRP, aka NUREG-0800) a document first written in the 1970s and recently (March 2007) updated for the first time in 25 years for applicability to new license applications. The SRP is written as guidance for the NRC staff in

reviewing an SAR, however, it has the effect of also providing guidance to the applicant as to what should be in the SAR and hence, how the reactor should be designed. Indeed, an applicant (as specified in 10CFR50.34, “Contents of Applications; Technical Information”) must “provide an evaluation of the facility against the SRP.” An applicant has the option of proposing a different approach but knows that this might require reversing a long-standing regulatory position. The SRP in turn refers to Regulatory Guides and Branch Technical Positions which further codify what is expected of the licensee.

There are other guidance documents that also influence reactor design. One of the most important of these is the Regulatory Guide (RG) entitled “Standard Format and Content of Safety Analysis Reports for Nuclear Power Plants (LWR Edition)” [originally RG 1.70, and now published as RG 1.206 for combined construction and operating license (COL) applications]. This guide provides guidance on what information should be in the SAR and therefore, indirectly, says something about reactor design. Other relevant documents are: 10CFR50 Appendix B, “Quality Assurance Criteria for Nuclear Power Plants and Fuel Reprocessing Plants;” and the “Standard Technical Specifications” that are approved by the NRC for each reactor vendor.

There is also an influence from “industry” consensus standards that have been written by subject matter experts that may come from either vendors, licensees, national and private laboratories, consultants, and/or the NRC. These standards have been referenced directly in the SRP and/or have been used by the licensee and referenced in the SAR. Lastly, the vendors and licensees that are directly involved with reactor design may have their own internal requirements that impact reactor design.

The result of all these influences is the description of reactor and other system designs in the SAR. Just as significant is the way in which the reactor design is verified during operation. This is done through the testing requirements found in Chapter 14 (“Initial Test Program and ITAAC-Design Certification”) of the SAR and the surveillance requirements found in the Tech Specs. The latter are formally Chapter 16 of the SAR but also usually an appendix to the license itself. Since the core design may change with each reload, the Tech Specs refer to the Core Operating Limits Report (COLR) issued for a particular reload.

^{*} NRC documents referenced herein can be found at <http://www.nrc.gov>.

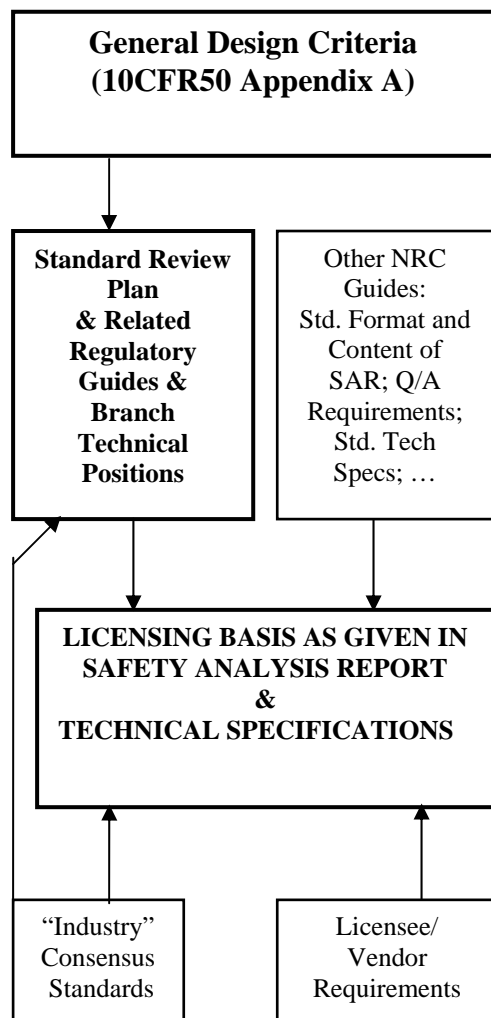


Figure 1 NRC General Approach to Reactor Design Control

2.2. Application to the MTC

It is instructive to show one example of the application of the aforementioned requirements and guidance; namely, the moderator temperature coefficient (MTC) for a pressurized water reactor (PWR). Figure 2 shows how design of the MTC is determined using the same influences shown in Figure 1.

The two GDC that are relevant are GDC 10 and 11:

GDC-10 Reactor Design: The reactor core and associated coolant, control, and protection systems shall be designed with appropriate margin to assure that specified acceptable fuel design limits are not exceeded during any condition of normal operation, including the effects of anticipated operational occurrences.

GDC-11 Reactor Inherent Protection: The reactor core and associated coolant systems shall be designed so that in the power operating range the net effect of the prompt inherent nuclear feedback characteristics tends to compensate for a rapid increase in reactivity.

The MTC impacts the core response to various anticipated operational occurrences and, therefore, helps determine if specified acceptable fuel design limits (SAFDLs) are not exceeded. Hence, it is clear that GDC-10 applies. GDC-11 has always been interpreted as stating that the power coefficient of reactivity should be negative and since the MTC has an impact on the power coefficient (albeit the most important component is usually the fuel temperature coefficient) it is impacted by this GDC as well.

The section of the SRP that applies to the design of the MTC is Section 4.3, "Nuclear Design." This section refers to GDC-10 and GDC-11 (and others). With respect to reactivity coefficients the primary guidance is that the licensee must consider all reactor states (cold shutdown through full power, the extremes reached during a transient/accident, different times within a fuel cycle, different control rod patterns, etc.); the coefficients used in analyses must be shown to be conservative; and an uncertainty analysis for nominal values must be carried out. For the MTC, the latter can be done by comparing calculated values with measured values.

It is noted in SRP Section 4.3 that in conjunction with satisfying GDC-11: "There are no criteria that explicitly establish acceptable ranges of [reactivity] coefficient values or preclude the acceptability of a positive MTC such as may exist in PWRs at beginning of core life." However, it does state that "The MTC should be non-positive over the entire fuel cycle when the reactor is at a significant power level."

Other guidance that is important for the MTC has to do with verification. In Section 14, Inspections, Tests, Analyses, and Acceptance Criteria (ITAAC) are discussed generically. Detailed guidance is found in "Standard Technical Specifications" issued by the NRC for each reactor

vendor and then in the Tech Specs for each plant. The Tech Specs refer to the COLRs which are

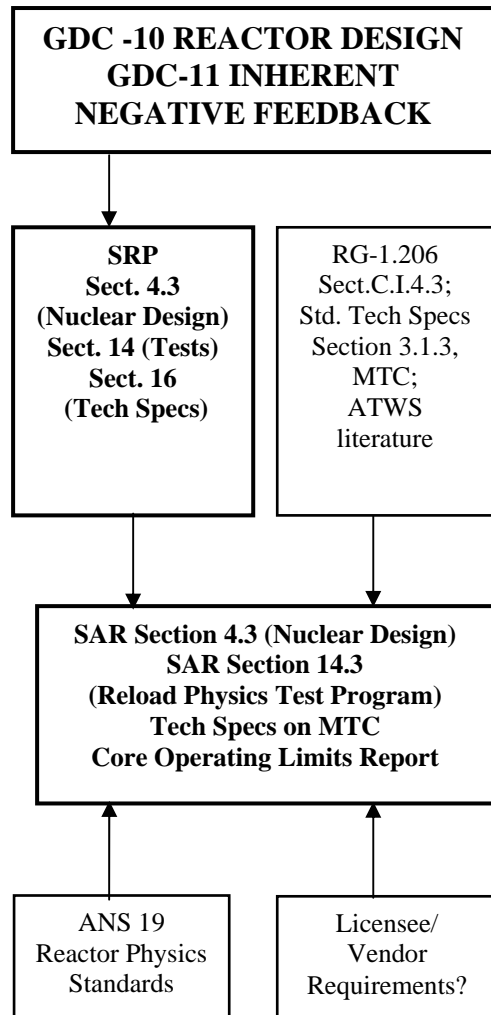


Figure 2 NRC Approach to MTC Design Control

issued every cycle with the specifications for the MTC and the surveillance requirements.

Information on the MTC that is given in the COLR includes the lower bound (largest magnitude of a negative value). This is influenced by the response of the reactor to a steamline break which cools the secondary and hence, also the primary coolant. The cooling adds reactivity because the MTC is negative, and although injection of additional soluble boron is expected, the concern is that the reactivity balance, even with all control banks inserted, can lead to a recriticality. The more negative the MTC, the greater the potential for a problem and hence the lower bound.

The COLR also specifies an upper bound on the MTC as a function of power level. This upper limit must be no larger than zero at 100% of rated power as stated in the SRP. (Hence, the largest value is really the smallest magnitude of the negative MTC.) How large it might be is influenced by the core response to transients/accidents and to anticipated transients without scram (ATWS). In an ATWS initiated by a loss of feedwater, the primary coolant temperature increases. Hence, the larger the MTC, (smallest magnitude but less than zero), the less of a mitigating factor it is because it is less effective in lowering the power. The lower the MTC (negative with large absolute value) the more power will be reduced as the primary heats up and this would help prevent the increase in pressure (due to the increase in primary temperature) from exceeding limits.

The COLR also specifies the surveillance requirements for the MTC. Since the MTC is the one reactivity coefficient that is straightforward to measure, this is an important means of verifying the nuclear design

There are consensus standards that have been developed by the American Nuclear Society (ANS), and then approved by the American National Standards Institute (ANSI), which are relevant to the MTC. "Calculation and Measurement of the Moderator Temperature Coefficient of Reactivity in Water Moderated Power Reactors," ANSI/ANS-19.11-2002 discusses the measurement at power conditions as well as the calculation of the MTC and "Reload Startup Physics Tests for Pressurized Water Reactors," ANSI/ANS-19.6.1-2005, discusses the measurement of the isothermal temperature coefficient at hot zero power conditions. Although these standards are relevant and have been used by licensees (and ANSI/ANS-19.6.1 has been referenced in SARs), they are not referenced in the SRP. Note too that other reactor physics standards for the calculation of parameters exist; however, they do not impose *requirements/guidance* for those parameters.

The box shown in Figure 2 that indicates licensee/vendor requirements refers to design control procedures that are used in industry. They are usually proprietary and hence, they have not been surveyed for this paper.

3. Relation to the approach by the IAEA

The IAEA publishes "Safety Standards" which include "Safety Fundamentals," "Safety

Requirements,” and “Safety Guides.” These are not consensus standards of the same type as those produced by, for example ANSI, or the International Organization for Standardization (ISO), nor are they legally binding on member states. They can be very useful for those countries that have not developed their own literature on the subject or as further support for existing regulatory documents, or in either case, as the basis for more detailed requirements. With respect to reactor physics there are four documents of interest. In the following we consider these documents in the context of the MTC.

“Safety of Nuclear Power Plants: Design” (IAEA, 2000) applies to water cooled reactors [light water reactors (LWRs) and heavy water reactors (HWRs)]. This is a wide ranging document which provides requirements similar to that provided in the NRC’s GDC. Under a section on the design of “Reactor Core and Associated Features” there are requirements for: General Design, Fuel Elements and Assemblies, Control of the Reactor Core, and Reactor Shutdown, all of which impact the neutronic design.

Consider the requirements most directly related to reactivity insertion or feedback and hence the MTC. (The numbering is from the original document.)

6.1 The reactor core and associated coolant, control and protection systems shall be designed with appropriate margins to ensure that the specified design limits are not exceeded and that radiation safety standards are applied in all operational states and in design basis accidents, with account taken of the existing uncertainties.

6.3 The maximum degree of positive reactivity and its maximum rate of increase by insertion in operational states and design basis accidents shall be limited so that no resultant failure of the reactor pressure boundary will occur, cooling capability will be maintained and no significant damage will occur to the reactor core.

6.4 It shall be ensured in the design that the possibility of recriticality or reactivity excursion following a postulated initiating event is minimized.

6.8 Specified fuel design limits, including permissible leakage of fission products, shall not be exceeded in normal operation, and it shall be ensured that operational states that may be imposed in anticipated operational occurrences cause no significant further deterioration. Leakage of fission products shall be restricted by design limits and kept to a minimum.

6.9 Fuel Assemblies shall be designed to permit adequate inspection of their structure and component parts after irradiation. In design basis accidents, the fuel elements shall remain in position and shall not suffer distortion to an extent that would render post-accident core cooling insufficiently effective; and the specified limits for fuel elements for design basis accidents shall not be exceeded.

6.15 At least one of the two systems shall be, on its own, capable of quickly rendering the nuclear reactor subcritical by an adequate margin from operational states and in design basis accidents, on the assumption of a single failure. Exceptionally, a transient recriticality may be permitted provided that the specified fuel and component limits are not exceeded.

Paragraphs 6.1, 6.8, and 6.9 are general requirements on plant response to transients and accidents and hence to reactivity feedback and the MTC. In particular, the MTC is most important in anticipated operational occurrences as cited in §6.8 which is analogous to GDC-10. More specific acceptance criteria for transients/accidents are provided for PWRs in an IAEA “Safety Report” (IAEA, 2003). The Safety Reports Series are informational publications and do not establish requirements or make recommendations. Nevertheless, the acceptance criteria enumerated in them are quite comprehensive and could form the basis for regulatory guidance.

Paragraph 6.3 above, addresses the amount of positive reactivity and rate of insertion that is allowed. This applies specifically to control elements in the core but does not preclude consideration of reactivity inserted by, for example, the entrance of cold water into a core with a negative MTC.

Paragraph 6.4 provides further limits on reactivity. The possibility of recriticality implies shutdown first, e.g., as in the steamline break scenario discussed above. The possibility of a reactivity excursion for a PWR could be the injection of cold and/or unborated water into the core. This paragraph, however, is somewhat contradicted by §6.15 which allows for recriticality during an event.

There are no IAEA requirements for a negative power coefficient or something akin to the GDC-11 requirement that there be prompt inherent nuclear feedback that compensates for a reactivity insertion. Instead, this is treated in a guidance document.

The Safety Guide pertaining to neutronic design that follows from the above IAEA Safety Requirements document is “Design of the Reactor Core for Nuclear Power Plants” (IAEA, 2005) and it is also applicable to both LWRs and HWRs. This document provides more guidance but still at a level that is not prescriptive to the extent that it could be. With respect to the examples above of IAEA requirements for reactivity feedback an important statement is:

2.11 The design of the reactor core should be such that the feedback characteristics of the core rapidly compensate for an increase in reactivity. The reactor power should be controlled by a combination of the inherent neutronic characteristics of the reactor core, its thermal-hydraulic characteristics and the capability of the control and shutdown systems to actuate for all operational states and in design basis accident conditions...

The first sentence of §2.11 clearly states the need for a negative power coefficient. However, it seems to be mitigated by the more lenient language in the second sentence and in the IAEA Safety Requirements document quoted above. The latter places the onus on meeting an acceptable fuel limit rather than on requiring negative feedback during a reactivity insertion event. Again, however, the importance to the MTC may be minimal when it is only a minor contributor to the power coefficient.

More specific information on the MTC is found in this guideline in Appendix I. One of the significant comments made therein is:

However, a slightly positive temperature coefficient of reactivity for the coolant-moderator is acceptable if the overall feedback effect on reactivity with temperature is sufficiently negative to limit the power increase to acceptable values.

The third IAEA document that is relevant is “Format and Content of the Safety Analysis Report for Nuclear Power Plants” (IAEA, 2004). It is analogous to the NRC Regulatory Guides mentioned above. It provides general guidance for documenting design but no specific requirements/guidance on what that design should include.

“Core Management and Fuel Handling for Nuclear Power Plants” (IAEA, 2002) is the fourth relevant IAEA document. It deals mostly with subjects not directly related to neutronic design. However, it does mention nuclear parameters that are to be considered in the design and also suggests tests which can be used to verify core design. As

with the previous guide, with respect to the MTC only general information is presented, i.e., no specific requirements/guidance is provided.

4. Concluding Remarks

Reactor physics design is influenced by the NRC through high level criteria/requirements and very specific guidance that comes from several documents of which the GDC and the SRP are two of the most important. The design is documented in the SAR which is a licensing-basis document. The verification of the design is specified in NRC guidance documents and then further bolstered by the NRC’s inspection program which provides assurance that Tech Specs are being followed.

The requirements/guidance for the MTC are compatible with international norms as specified by the IAEA. In general this is true for other neutronic parameters, however, there are exceptions. An example is the requirement for a negative power coefficient as delineated in GDC-11. For the IAEA this issue is treated as part of guidance which emphasizes compliance with fuel limits rather than inherent feedback.

In summary, this paper lays out the requirements/guidance for reactor physics design in the U.S. It is of interest because of the increase in new reactor design, licensing, construction, and operation that is underway and because of the continuing interest in normalizing such requirements/guidance internationally.

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